The global environmental paw print of pet food

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Abstract

Global pet ownership, especially of cats and dogs, is rising with income growth, and so too are the environmental impacts associated with their food. The global extent of these impacts has not been quantified, and existing national assessments are potentially biased due to the way in which they account for the relative impacts of constituent animal by-products (ABPs). ABPs typically have lower value than other animal products (i.e. meat, milk and eggs), but are nevertheless associated with non-negligible environmental impacts. Here we present the first global environmental impact assessment of pet food. The approach is novel in applying an economic value allocation approach to the impact of ABPs and other animal products to represent better the environmental burden. We find annual global dry pet food production is associated with 56 – 151 Mt CO_2 equivalent emissions (1.1% - 2.9% of global agricultural emissions), 41 – 58 Mha agricultural land-use (0.8 – 1.2% of global agricultural land use) and 5 – 11 km^3 freshwater use (0.2 – 0.4% of water extraction of agriculture). These impacts are equivalent to an environmental footprint of around twicethe UK land area, and would make greenhouse gas emission from pet food around the 60th highest emitting country, or equivalent to total emissions from countries such as Mozambique or the Philippines. These results indicate that rising pet food demand should be included in the broader global debate about food system sustainability.

Keywords

Environmental footprint; Food Security; Greenhouse Gas Emissions; Land Use; Water Use; Animal by-products

1 Introduction

Estimates of global companion animal (i.e. pet) ownership suggest that over 50% of all households own a cat or dog, with pet populations in the US alone having tripled to around 157 million since the 1970s (WWF, 2016; GfK, 2016). This global trend in ownership mirrors income and related demographic change in terms of family size, people living alone, increased life expectancy and urbanisation) as well as changing preferences and general anthropomorphism of companion animals. In contrast to the debate about the increasing global environmental impact of human food systems, and livestock products in particular (Alexander *et al.*, 2015; Hallström *et al.*, 2015; Clark and Tilman, 2017; Poore and Nemecek, 2018), the environmental impacts of pets - the 'environmental paw print' (Martens et al., 2019) - has received much less attention. Yet, a potentially increasing burden associated with feeding pets suggests that companion animal food demand needs to be accounted for alongside other food system challenges.

Impact assessments of pet diets have been conducted for the USA (Okin, 2017), Japan (Su and Martens, 2018), and China (Su *et al.*, 2018), but there has been no global assessment. A reason for this research gap may be that pet food includes animal by-products (ABPs), which could lead to the incorrect perception that associated impacts will be negligible. ABPs are a primary component of commercial pet foods, with 25 million tonnes rendered each year in the US alone (Meeker, 2006; Meeker and Meisinger, 2015). ABPs provide an affordable source of animal protein and are believed to have contributed to the growth of the pet food industry (Corbin, 1992).

ABPs are not typically consumed by humans and currently have limited value in the human food market (Garnett, 2007). However, ABPs are not valueless, and provide a financial return to the livestock industry that incentivises increased livestock production, with implications for environmental impacts (Food Climate Research Network, 2015). Furthermore, alternative uses of

ABPs in fertiliser and as biofuel are feasible (Ramirez et al., 2012), implying a shadow value of environmental impacts corresponding to their potential opportunity uses. If pet foods were a use for otherwise unwanted, and valueless, ABPs, this would imply no associated environmental impacts. Existing pet food impact studies (Okin, 2017; Su and Martens, 2018; Su *et al.*, 2018) indiscriminately assign environmental impact equally to all animal-derived product mass, implying 1kg of prime steak has the equivalent impact of 1kg of ABP. Conversely to the assumption of zero impact, this greatly over-estimates the environmental impacts of most pet foods.

This study estimates the global environmental impact of pet food on land use, greenhouse-gas (GHG) emissions and freshwater abstraction. We use an economic valuation approach to allocate the impact of ABPs and so derive an alternative representation of the environmental burden (Alexander et al., 2017b). We focus on cats and dogs, which constitute 95% of global pet food sales (Euromonitor, 2019a). We quantify the resource use and environmental impacts associated with different commodities and ingredients in pet food on a value basis, distinguishing ABPs from standard meat commodities and, assigning impacts more accurately than previous studies. We also estimate a globally representative pet food composition and compare environmental footprint results with studies where impacts are allocated by mass. Improved estimation of environmental impacts associated with pet food production allow their resource use to be considered more consistently alongside other parts of the global food system.

2 Materials and methods

In summary, we calculate the environmental impact for land use, GHG emissions and freshwater of dry pet food using pet food ingredient data (Okin, 2017) and results from existing studies of the environmental impacts of constituent foods (Alexander et al., 2016; FAO, 2017; Mekonnen and Hoekstra, 2010; Poore and Nemecek, 2018; Springmann et al., 2018, 2017). An economic value allocated method was used to attribute impacts to ABPs, and the results compared with mass allocation used in previous national studies (Okin, 2017; Su and Martens, 2018; Su *et al.*, 2018). Uncertainty was explored by considering differences between environmental impact studies, and by varying ABP price and percentage of animal live weight, the ABP allocation assumption and pet food ingredient weighting. Further details of these steps are given in the following section.

2.1 Pet food composition

There is a lack of data on the composition of pet food, with no dataset with global coverage similar to that held by the FAO for human foods. We therefore estimate ingredient proportions in pet food using data (Okin, 2017), one of the few datasets available, which lists the first five ingredients from 281 dry pet foods in the US market in four categories: premium dog food (n = 100), premium cat food (n = 163), market-leading dog food (n = 9), and market-leading cat food (n = 9). Due to a lack of data for other regions, we apply these ingredients to global data on pet food production. US pet food accounts for a third (33%) of global sales, Europe approximately another third (32%), the remainder is divided predominately between Latin America 21% and Asia-Pacific 12% (Africa and the Middle East respectively have only 2% and <1%). Dry food constitutes 79% of US pet food sales (Statista, 2018). Brands that make up the majority of US sales (APPA, 2015), are also available in Europe (e.g. Purina, IAMS and Pedigree) with Purina being disturbed in all regions. This suggests similarity between pet food compositions in the US and Europe (two thirds of global pet foods), although there may be greater differences in other regions, in our view this assumption provides a reasonable global estimate. We use ingredient weighting to explore the potential uncertainty related to this assumption.

Each of the approximately 1400 ingredient entries (5 ingredients for each of the 281 products) were assigned to twenty-four commodity groups, with market-leading foods containing fourteen commodity groups, i.e., lamb, poultry, bovine ABP, poultry ABP, unspecified ABP, maize, wheat, oats and barley, rice, brewers rice, other cereals, soybean meal, corn gluten meal and other vegetables. Premium food included all twenty-four commodities, and additionally beef, pork, eggs, fish, lamb ABP, pork ABP, fish ABP, pulses, starchy roots, pulses and vegetal oil. To identify ingredients as an ABP, we use the United States Department of Agriculture (USDA) definition as “hides, skins, fats, bones and edible/inedible offal" (Hahn, 2004). Water was listed as an ingredient in 15 products, and was removed in each occurrence, with subsequent ingredients increased in ranking, assuming the water used has a negligible environmental footprint. The ingredient list for all 281 pet foods and mapping to the commodity groups is presented in the supplementary material (Table S1).

Assumed ingredient weightings and sensitivity analysis

Okin (2017) assumes that the first five ingredients are equally weighted, constituting the entire pet food mass (i.e. each of the five ingredients listed account for 20% of the mass). Ingredients are listed in descending order of weight; an assumption that is at the most extreme end of what is possible. As this allocation is unknown and will vary by product, we consider a range of ratios between the ingredients that we express as an apportionment ratio between successive ingredients. For example, given a ratio of 1.5, the ingredient listed first is 1.5 times that of the second ingredient. A ratio of 1.5, the median parameter value in the analysis, gives the ingredients a percentage of 38.4% for the first listed ingredient, 25.6% for the second, and 17.1%, 11.4% and 7.6%, respectively, for the subsequent three. Uncertainty is considered by varying the ratio between successive ingredients over the range 1 to 2, with 1 being equivalent to the Okin (2017) assumption. Mean ingredient proportion is calculated for each of the four pet food categories as the average of proportions in each of the foods in that category. Unspecified ABP, e.g. lungs, heart, kidneys, were distributed among the specified ABP types (i.e. poultry, pork lamb and beef) in proportion to use of those ingredients in each pet food category.

Pet food mass

Alltech (2019) used a global feed survey to estimate a total global pet food production of 26.6 million tonnes (Mt). The survey reports that North America is responsible for 8.8 Mt of pet food production. As a cross check, applying an average gross energy of cat and dog food of 461 kcal/100 grams (Davies et al., 2017) implies 170 Petajoules (PJ) within US pet food. This accords with dog and cat energy estimates in the US of 203 PJ/year (Okin, 2017). We use this global figure disaggregated into the 4 categories of food, that is, into premium and market-leading for both cats and dogs. We weight the global quantity according to averaged cat and dog premium (34%) and market-leading (66%) customer preferences from the American Pet Products Association (APPA) survey (*APPA*, 2015). This implies 8.5 and 16.5 Mt of premium and market-leading pet food respectively. Each of these quantities is weighted according to US dog (78%) and cat (22%) energy consumption (Okin, 2017), to give 2Mt premium cat food, 7.1 Mt premium dog food, 3.9 Mt market-leading cat food and 13.7 Mt market-leading dog food. These quantities are applied to the specific pet food category ingredients to calculate commodities used for each type.

2.2 Environmental footprints of ingredients

A commodity-specific footprint for GHG emissions, land use and water use were estimated for the pet food ingredients from a range of sources (Alexander et al., 2016; FAO, 2017; Mekonnen and Hoekstra, 2010; Poore and Nemecek, 2018; Springmann et al., 2018, 2017). These values are given in the supplementary material (Table S2) and derived as described below. Fish and fish ABP (1.6% of total pet food mass) were here assigned zero environmental footprint as there are insufficient data for a robust comparison. Similarly, ingredients that were unmapped, e.g. flavouring and salt, which in aggregate comprised 0.5% of the mass, were assigned zero environmental costs.

GHG emissions

The GHG emissions footprint is reported in carbon dioxide equivalents (CO_2 eq). Commodity-specific emission factors from 4 sources are used in the Global Livestock Emissions Assessment Model (GLEAM) (FAO, 2017), Springmann *et al.* (Springmann et al., 2018, 2017), and Poore and Nemecek (2018) to calculate emissions intensities of each ingredient. GLEAM (FAO, 2017) emission factors are per weight of protein. Emissions on a per weight basis (kg CO_2 eq/kg) were produced by multiplying the USDA (2020a) protein contents (kg/kg) by the emissions rate (kg CO_2 eq/kg protein) for each animal product. GLEAM (FAO, 2017) only provide livestock emission intensities; these are supplemented with non-animal emission intensities from Springmann *et al.* (2017). Poore and Nemecek (2018) provide emission factors (as well as land and water use rates) for beef from dairy herds and beef from beef herds. We used combined beef environmental impact factors weighted by production system, assuming 22% of beef production is sourced from dairy cows (USDA, 2017).

Land use

We calculated two cropland footprints from data from two studies, Springmann *et al.* (2018) and Alexander *et al.* (2016). Two studies were also used for agricultural land use (i.e. additionally including pasture) footprints, Poore and Nemecek (2018) and Alexander *et al.* (2016). The difference between cropland and agricultural land arises because Springmann *et al.* (2018) only provide cropland use, while Poore and Nemecek (2018) provide agricultural areas, but do not provide a disaggregation between cropland and pasture areas.

Freshwater abstraction

Water use is here focussed on freshwater abstraction or a 'blue' water footprint (Mekonnen and Hoekstra, 2010), defined as 'consumption of blue water resources (surface and groundwater) along the supply chain of a product'. Freshwater withdrawal factors were derived from three studies, (Mekonnen and Hoekstra (2010), Poore and Nemecek (2018) and Springmann et al. (2018).

Accounting for by-products

Environmental footprints for by-product are not available from the sources described above. For example, while estimates for beef (or bovine meat) impacts are provided, those for bovine ABP are not. Previous pet food studies (Okin, 2017; Su and Martens, 2018; Su *et al.*, 2018) have applied the same rates per kg for by-products as for the associated meat, i.e. they apply beef emissions for bovine ABP. This mass allocation approach is, in our view, flawed in its application of equal environmental impact rates for ABPs as for higher value meat products. We therefore use an economic value allocation method, where the environmental impact of producing an animal are allocated in the same proportion as the value of the products. The approach uses the prices and quantities of meat and ABP for each animal type. However, we also calculate environmental impacts using the mass allocation approach to allow comparison with previous studies and to establish the scale of the difference between the by-product allocation approaches.

The environmental impact factors (i.e. GHG emissions, land or water used) of by-products using an economic value allocation are calculated as per Equation 1.

$$E_{ABP} = \frac{R.P_{ABP}}{(1-\mathrm{R}).P_{ABP} + \mathrm{R}.P_{meat}} E_{meat} \tag{1}$$

where, E_{ABP} is environmental impact factor for the ABP; E_{Meat} is reported environmental impact factor for meats; R is the dressing percentage, i.e. the percentage of animal carcass weight with ABP removed; P_{ABP} is ABP price; and, P_{Meat} is net farm value. Net farm value is described as `gross farm value minus the value of by-products and represents the value of meat to the farmer' (Hahn, 2004). To avoid potential double counting of impacts the meat environmental impact factors are adjusted, such that the whole animal footprint is unchanged, but allocated between ABP and meat based on value (see SI for derivations). The prices and dressing percentages (FAO, 2017; Swisher, 2017; USDA, 2020b, 2020c) used are given in Table S3.

Crop by-products are found in the market-leading, but not premium, food ingredient lists analysed, e.g. soybean meal, corn gluten meal and brewers rice. In an equivalent manner as with ABP, we use an economic value allocation for these processed crop products. For example, when soybeans are processed approximately four times more meal is produced than oil, but as the price per kg of oil is close to four times greater than the meal the total values contained in both products is similar (Alexander et al., 2016). In the case of maize, the processing produces corn starch, corn gluten feed, corn gluten meal, and corn oil, but the same value allocation process is applied. Tables S4-6 give the adjustments calculated and applied for the crop by-products.

2.3 Uncertainty quantification

We used a Monte Carlo (n = 1000) approach to explore the results under uncertainty in pet food ingredients and the by-product allocation to environmental impacts. The ratio of percentage quantity in the pet food between successive ingredients was sampled from a uniform distribution from 1 to 2. We also considered uncertainty in both the livestock dressing percentage and by-product prices for each animal product and associated ABP, using an adjustment multiple applied to the baseline data (Table S3), sampled from uniform distribution from 0.5 to 1.5.

3 Results

3.1 Pet food composition

ABPs constitute 32.0% of total dry pet food by mass, animal products 16.3%, fish with fish by-product 3.1% and crop products 47.9% at median parameter values (Figure 1 & S1 and Table S7). Of the crop products, maize dominates with 20.5% (42.7% of crops), with corn gluten meal and soybean meal both having 6.1% (12.8% of crops) each. The most prominent primary animal commodity by mass is poultry meat at 10.2%, and also for ABPs with 23.4% from poultry by-products. Using an equal 20% proportion of commodities between the 5 ingredients (i.e. ratio between successive ingredients of 1) does not change the division between categories substantially, ABP percentage is 35.5%, animal products 9.8% and crops 52.6%, but it does spread the commodities used more evenly within these groups, e.g. maize remains the largest crop but drops to 24.5% of crops. The trend of increasing concentration in fewer commodities continues with higher ratios between successive ingredients (Table S7 gives commodity quantities at ratio between successive ingredients of 1, 1.5 and 2).

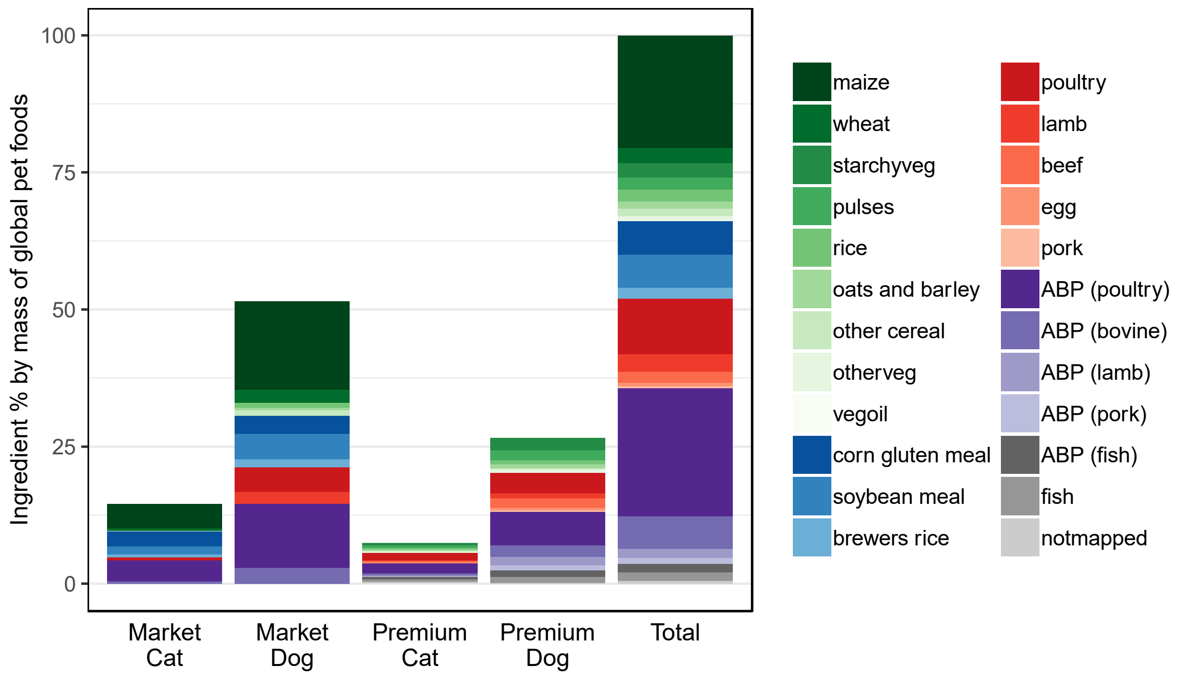

Figure 1. Median constituent breakdown of global pet food, crop and vegetables (greens), crop by-product (blues), animal products (reds), animal by-product (purples), and others (greys), by descending mass in each category.

3.2 Environmental paw prints

Our assessment of global dry pet food impact on GHG emissions, including appropriate value allocation for ABPs, indicates global annual emissions of 56.3 – 151.2 Mt CO_2 eq (Figure 2, Table S8). The range in values derives from the four data sources considered, in each case with median parameter values for ABPs and ingredient apportionment. This suggests that pet food production is associated with 1.1% - 2.9% of global agricultural GHG emissions, assuming global agricultural GHG emissions at 5,189 Mt CO_2 eq (FAOSTAT, 2019). A mass allocation approach, applying impacts equally to by-products and primary products, as has been done in previous studies, produces annual GHG emissions approximately 2.3 times greater (127 – 347 Mt CO_2 eq) than estimates with appropriate valuation of ABPs as provided here (Figure 2). The substantial reduction in the emissions associated with ABPs under an economic allocation method results in ABPs dropping from 59-64% to 12-18% of the total, and animal products increasing from 30-38% to 66-82% compared to the mass allocation approach.

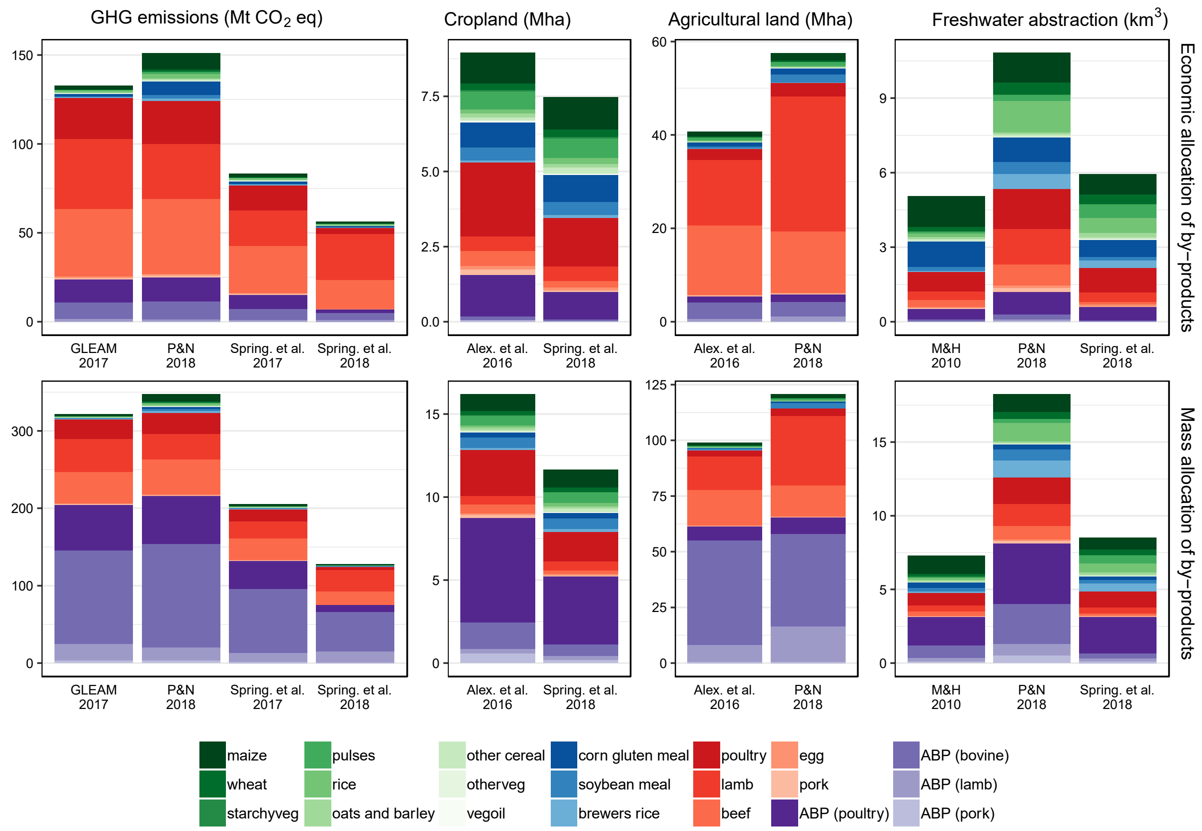

Figure 2. Global GHG emissions, land use and freshwater abstraction paw prints for pet food across all impact rate source studies. Environmental impacts calculated using an economic value allocation method are shown in the top row, and environmental impacts calculated using a mass allocation method in the bottom row. Impact data sources are abbreviated as: Alex. et al. 2016 (Alexander et al., 2016); GLEAM 2017 (FAO, 2017), M&H (Mekonnen and Hoekstra, 2010); P&N 2018 – (Poore and Nemecek, 2018); Spring. et al. 2017 - (Springmann et al., 2017).

Agricultural land used for global pet food production was 40.7 to 57.6 Million hectares (Mha) annually (Figure 2), representing 0.8 – 1.2% of global agricultural land use of 4869 Mha (FAOSTAT, 2019). Percentage cropland use associated with pet food was lower at 0.5 – 0.6% of global cropland area of 1,591 Mha (FAOSTAT, 2019), or 7.5-8.9 Mha. The mass allocation approach produces land use areas 2.1 – 2.4 times greater for total agricultural land use (99 – 121 Mha) and around 1.7 times greater for cropland-specific land use (11.7 – 16.2 Mha).

Freshwater abstraction associated with pet food ranged from 5.1 – 10.8 cubic kilometres (km^3) per year (Figure 2), equivalent to 0.2 – 0.4% of the global agricultural freshwater withdrawal of 2,769 km^3 (AQUASTAT, 2016). Equally weighting ABPs on a mass allocation basis produces freshwater withdrawals approximately 1.6 times greater (7.2 – 18.3 km^3) than median estimates with appropriate valuation of ABPs (Figure 2, Table S8). For GHG emission and agricultural land, the majority (~70%) of impacts come from animal products, with an economic allocation approach for by-products, with ABPs adding further to the contribution associated with livestock. However, for cropland and water approximately 50-60% of impacts are associated with the crop products within pet foods.

3.3 Categories of pet food

The foods for different categories of markets of pet food (market-leading and premium) and target species (cat and dog), have distinctive ingredients (Figure 1), which give rise to some substantial differences in the environmental impacts per unit of mass (Figure 3). The higher proportions of meat content in the premium products and dog foods lead to greater GHG and agricultural land paw prints for these products. For example, for GHG emissions, premium brands had 3.3 times the emissions intensity of market-leading cat food and 2.3 times the emissions intensity of market-leading dog food. In aggregate, dog food emissions intensity was 1.6 times that of cat food. The total cropland and water use per kg were smaller, as the differential impacts between ingredient is lower than with GHG emissions or agricultural land use.

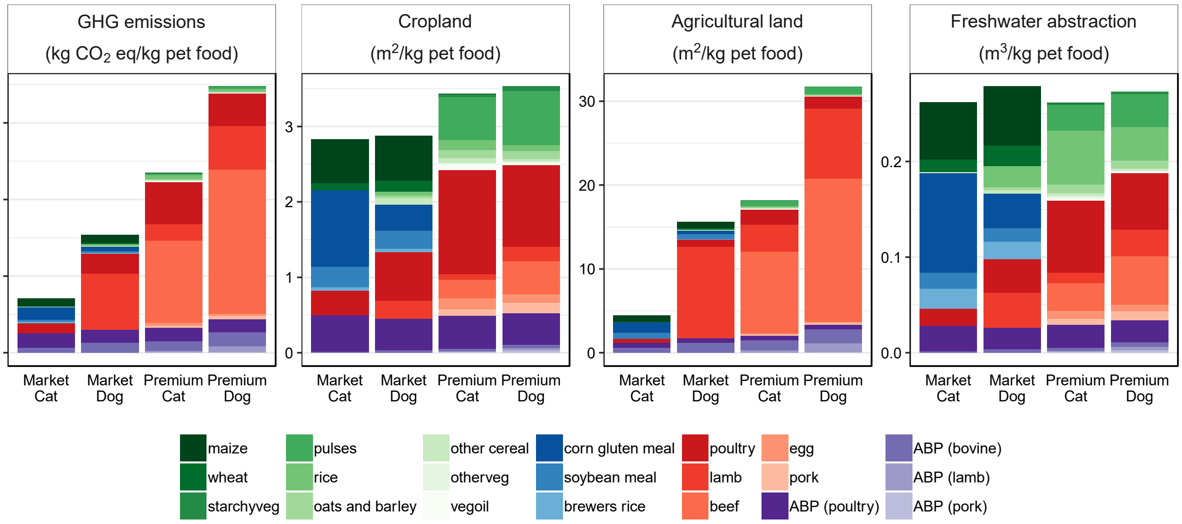

Figure 3. Rate of environmental impact (GHG emissions, land use and freshwater abstraction) per kg of by pet food type, as mean values across data sources.

3.4 Uncertainty in environmental impacts

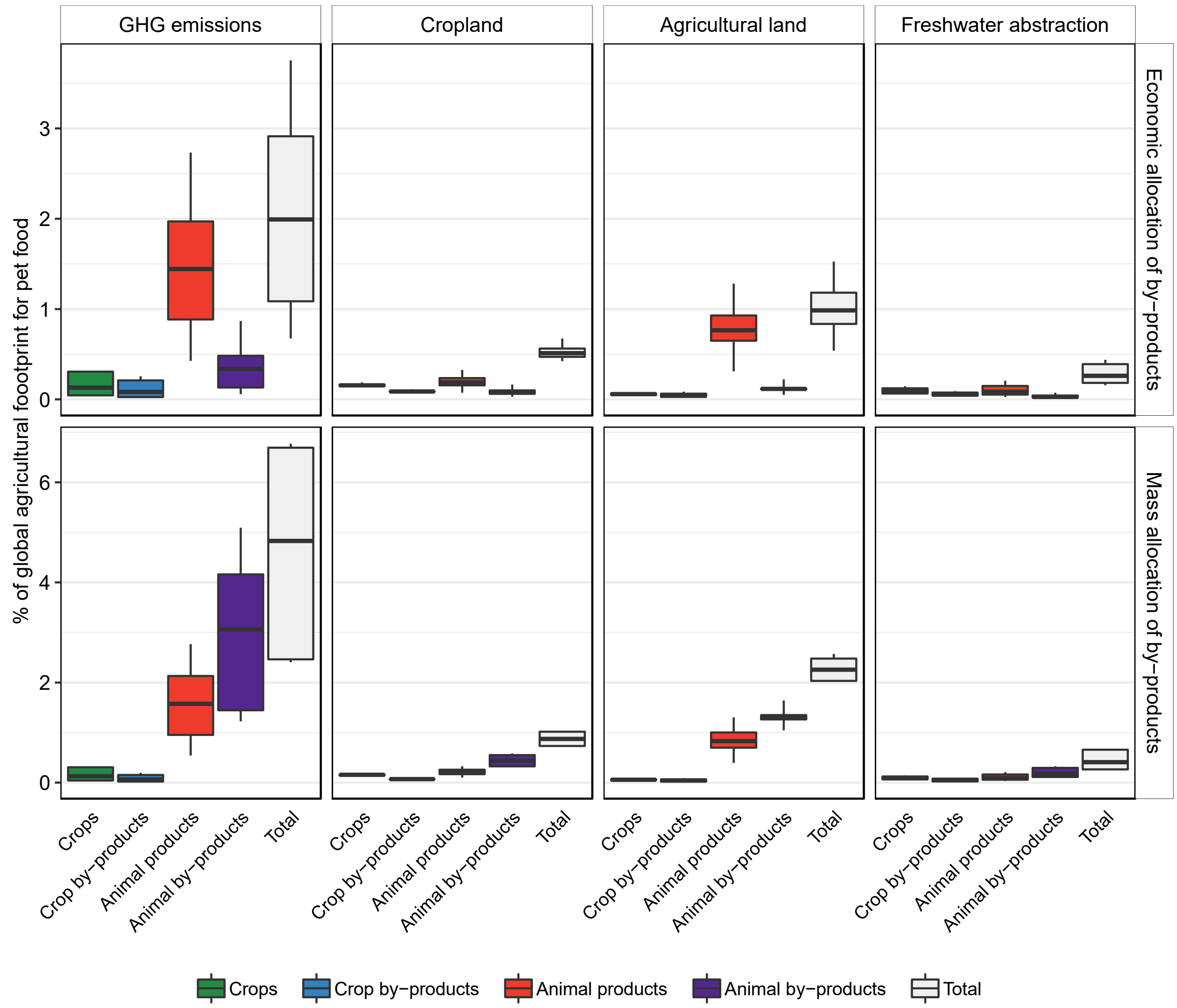

Figure 4. Global GHG emissions, land use and freshwater abstraction for pet food expressed as a percentage of global agricultural totals. Environmental impacts calculated using an economic value allocation method are given in the top row, and environmental impacts calculated using a mass allocation method in the bottom row. Boxplot distributions are produced from Monte Carlo samples of ingredient apportionment, dressing percentage and ABP price (n = 1000), and shows median, hinges for the environmental impact source and whiskers for total range.

The sensitivity analysis considered variation in prices in commodities, live weight percentages and ingredient apportionment. It resulted in a range of annual GHG emissions from global dry pet food of 36.3 – 185.2 Mt CO_2 eq (0.7% – 3.6% of global agricultural emissions) using the economic by-product allocation approach. This increases to 2.4 – 6.8% agricultural emissions using mass allocation of by-products. For cropland and agricultural land economic allocation the range was 6.8 – 10.3 Mha and 27.5 – 70.1 Mha (0.4 – 0.7% and 0.6 – 1.5%, respectively). Water use ranged from 4.5 km^3 to 11.9 km^3 (0.2 – 0.4% of global agricultural water withdrawals). Using percentage of global agricultural use as a metric, our results indicate that pet food consumption is responsible for relatively more GHG emissions than for land use or freshwater withdrawal (Figure 4). Freshwater abstraction (Mekonnen and Hoekstra, 2010; Poore and Nemecek, 2018) for pet food had the lowest percentage of the respective agricultural total.

4 Discussion

4.1 Comparison to previous pet food impact assessments

The limited data on pet food ingredients complicates estimation of detailed feed composition and thus the assessment of global impacts. Nonetheless, we observe consistency with other sources on pet food composition, which report ABP proportions (Walsh, 2014) and cereal-based product proportions (Murray et al., 1997) of 25 – 40% and 40%. These values are in line with our estimates of the proportion of ABPs (31.6 – 35.5%) and cereal-based products (27.6 – 32.6%). However, the environmental impacts associated with pet foods found here are lower than previous country-level estimates (Okin, 2017; Su and Martens, 2018; Su et al. , 2018). A previous assessment of the land use, water use and fossil fuel emissions paw prints of cats and dogs in the US suggested these were equivalent to 25 – 30% of those for the US human population (Okin, 2017). Another study in China reported land-use and carbon emission paw prints equivalent to 5.1 – 17.8% and 2.5 – 7.8% of the Chinese human population, respectively (Su et al., 2018). A key methodological difference is our economic value allocation of ABPs, with our results range for emissions using the mass allocation approach overlapping with those previously published for China. US estimates may be greater due to the higher rates of pet ownership than the global average as well as being the largest pet food market in the world (Alltech, 2019).

There are other methodological differences between the study reported here and previous studies. An assumption of previous studies (Martens et al., 2019; Su et al., 2018; Su and Martens, 2018) on pet foods is that the composition can be split into animal and non-animal products, with a single commodity's use being representative of each group. For example, in the US study two categories (animal and non-animal products) are considered (Okin, 2017). Similarly, the assessment in China assumes all animal product consumption is chicken and all non-animal product consumption is cereals. Here we have taken a more detailed approach and consider 24 ingredients with different impact rates. This greater distinction of commodities is supported as some are responsible for disproportionately high environmental impacts. For example, beef and lamb combined constitute just 5% of the total pet food, but are responsible for around 50% of total GHG emissions and 70% of total land use (Figure 1 & 2).

We find a range of results by obtaining land, water or GHG commodity impacts from different studies (Alexander et al., 2016; FAO, 2017; Mekonnen and Hoekstra, 2010; Poore and Nemecek, 2018; Springmann et al., 2017) (Figure 2). The difference in results between the two studies used for both cropland and agricultural land areas is relatively high. GHG emission estimates using Poore and Nemecek (2018) and GLEAM (FAO, 2017) for animal product GHG emission rates mirrored each other closely across all parameter variations. However, emissions estimated using both Springmann *et al.* (2018, 2017) studies were low relative to the others, perhaps due to emission intensities for non-animal products not including emissions from land use change and post-farm emissions (Springmann et al., 2017). Freshwater abstraction results also showed substantial variation between source study data, with Poore and Nemecek (2018) appearing high relative to the other two studies.

However, given the small number of sources, it would be inappropriate to note anything more than that there is considerable uncertainty and variation in the results.

4.2 Limitations and the need for better data

The analysis here considers only the quantity of dry pet food globally, and therefore underestimates the true impact from feeding pets. While dry food constitutes up to 79% of US pet food sales (Statista, 2018), other pets consume commercially-produced wet pet foods, or eat leftovers or table scraps. These other sources of pet nutrition are not considered here, due to a lack of information. These other pet foods are likely to be different in composition to dry foods, and therefore it would be inappropriate to scale the analysis presented here to all pet foods. However, if the impacts of other pet foods were added to those of the commercially produced dry pet food assessed here, it would increase the overall environmental burden from feeding pets. Potentially many of the pets in the developing world are fed leftovers and food scraps, although without good data this is speculation. Su et al. (2018) states that land use and carbon emissions of an average sized dog in China relying on commercial dry pet food were three and eight times higher, respectively, than dogs relying on human leftover foods. However, this was without consideration of the reduced environmental footprints associated with ABPs.

While our study differentiates between ABP animal sources it makes no differentiation between specific ABP product and value can vary within even a single animal source. For example, US prices for pork by-products can vary from 19 cents/lb for kidneys to 97 cents/lb for ears (Marti et al., 2011). More information on the quantities of products being used in pet food would also be beneficial to ensure accurate estimates of common ingredients.

In this study, we use an economic allocation of impacts rather than the physical relationship between animal primary and by-product production. Allocation by economic value describes relationships between products that is more suited for use in systems that produce multiple goods with widely differing values per weight than mass allocation (Ardente and Cellura, 2012; Williams, A.G. Audsley, E. Sandars, 2006). However, with this approach prices and proportions of co-products can fluctuate and will alter the results. Prices of animal products and ABP may also vary between regions, which is not reflected in the single price used for each commodity in the analysis. Hence conducting a sensitivity analysis is important to explore the impact of uncertainty in prices. The results of the sensitivity analysis – covering a 50% increase or decrease in prices – suggest the range of results presented here would remain representative unless substantial shifts occur in future market conditions.

Alternative allocation methods to economic value and mass could have been used, but these have their own limitations. Calorific or protein content have been applied in previous food analyses (Alexander et al., 2017b; Smith et al., 2017). However, in the case of pet food, the difference between mass allocation and either calories or protein would be small. Pet food manufactures have clear incentives to choose ingredients that are low cost but high protein and calorific value, and therefore select products such as heart and kidney. These and other ABP used have protein and calorie contents that are similar (some higher and some lower) to those in meat (USDA, 2020a). This contrasts with the more than 10-fold difference in price between meat and ABPs. A second rationale for an economic allocation is that the study is framed to consider incentives created by global pet food on agricultural production. A change in revenue from livestock, due to a change in the price of any animal product would change the incentives and so shift the level of production and consequential environmental burdens. An economic allocation assigns these environmental burdens in proportions to the financial incentive that led to them. As a result, an economic allocation (unlike mass, protein or calories approaches) represents an increase in environmental impact between a pet food with large amounts of high value cuts of meats versus another that is mostly ABPs, where both have the same mass and nutrients content. Additionally, the economic allocation will produce the lowest paw prints of these approaches. Applying a conservative approach avoids over inflating or sensationalising the importance of pet foods impact.

We find a lack of information on the quantities of commodities found in pet food at a regional or global level necessitates our assumptions of the division between 5 ingredients. Reliable supply chain data for the pet food industry is required to further increase accuracy. The small number of previous pet food studies (Okin, 2017; Su and Martens, 2018; Su *et al.*, 2018) that do exist provide a coarser breakdown than is provided in our analysis (ABPs, cereal-based products and other), but nonetheless agree with our findings, as discussed above. While data that capture the regional variability in pet food ingredients would be preferred, applying US values globally nonetheless provides an initial impression of environmental impacts from global pet food.

The sensitivity analysis (Figure 4) produces large ranges of impacts, as a result of the cumulative uncertainty described above, but the conclusions, for example that feed of pets is a non-negligible contributor to environmental impacts, remain.

4.3 Future pet and human food choices

'Premiumization' of pet foods, i.e. a move to higher cost products with more expensive ingredients, is increasing and is the main driver of pet food growth in the developed world as motives influencing choice of pet food by owners' begin to mirror their own (Euromonitor, 2019b). One study found dog owners to be more consistent in buying healthy dog food than healthy human food (Tesfom and Birch, 2010). Younger generations in the US and other developed nations have lower birth rates and are waiting longer to have children (OECD, 2020). Instead, many people opt for pet ownership for companionship at a fraction of the price and responsibility (Bao and Schreer, 2016). Pets may fit in with modern societal norms focused on individual career development as opposed to familial priorities. This in turn may support continuation of the humanisation trend, over-consumption and pet obesity (Swanson et al., 2013). It has also been observed that raw meat diets (or diets of which a substantial proportion is raw meat) with inherently greater environmental impacts, have increased despite poor evidence that this can be a healthy diet for cats and dogs (van Bree et al., 2018). The true strength or significance of the effects mentioned is debatable. If these trends do affect environmental impacts associated with pet food, they may produce a negligible effect on a global scale. Growth of the middle classes in developing countries lags behind on the same trajectory as developed nations, moving from table scraps to any affordable branded pet food with a higher proportion of lower value animal and crop by-products.

Incorporating more edible ABPs into human diets could support more sustainable consumption of animal products whilst helping to address food insecurity (Alao et al., 2017). Increasing ABPs demand for human food consumption would be expected to reduce the available quantity for other uses, increase the value of ABPs and incentivise improved carcass utilisation (Garnett, 2007). Increased prices could increase the environmental impacts associated with ABPs (and commensurately reduce the impacts on other animal products), as ABPs would constitute a higher proportion of the total value of livestock-produced goods. The result could be an increase in the environmental impacts associated with pet food when using an economic allocation, in such a circumstance. The net environmental outcome would be expected to be positive if total livestock production was reduced through a human dietary substitution towards ABPs consumption from, for example, meat. Although per capita global animal product consumption is projected to increase in the future (Bodirsky et al., 2015), it remains an open question whether greater ABPs consumption would be acceptable in human diets.

4.4 Sustainable pet ownership?

Our results demonstrate substantial agricultural land, GHG emissions and water impacts from pet food. The role of pet food is seldom considered in the growing conversation on food production and consumption, and the public awareness of its implications. Data on pet food consumption are not collected to the same degree of accuracy as that of the commodities most commonly consumed by humans. Yet, there is cause to analyse consumption patterns of pets, to understand the scale of the environmental impacts and to instigate sustainable practices that mitigate associated harms.

Pets provide socio-psychological benefits for owners and functional support to the disabled, police and on farms (Bao and Schreer, 2016; Okin, 2017). These benefits are an important, though frequently non-market, counterpoint to any environmental burden attributed to the animal, which typically does not have agency in its feeding choices. Human attitudes to companion animals and their diets are culturally co-evolving, and increasing anthropomorphism has the potential to drive feeding decisions in different directions. With economic growth, pet feeding trends will likely be subsumed into the same sustainability considerations taken by everyday food choices of owners. Meanwhile, there is an observed dietary shift from table scraps or leftovers to commercial pet food with stated health benefits (Kharas, 2010). Sales of ‘natural’ pet foods, foods containing meat, whole grains and generally less by-products, more than doubled between 2008 and 2012 due to a growing belief that these foods are more nutritionally beneficial to pet health (Carter et al., 2014). The result may be one of owners purchasing cuts of higher-grade raw meat or packaged food with more ‘natural’ ingredients (Swanson et al., 2013), so increasing associated environmental impacts.

Interventions to foster sustainable pet ownership have to target the decisions made by owners. Affecting voluntary feeding choices by increasing owner awareness suggests an important role for feed manufacturers, although it is unclear whether the latter will be prepared to adopt further responsibility through improving existing labelling. Alternatively, it is possible to develop more mandatory and market-based incentives to nudge manufacturers and actual or potential pet owners towards less emission intensive companions or feeding options. Mandatory instruments can regulate for specific content, processes and labelling in manufacturing chains. They can also relate to the compulsory registration of pet ownership as a potential basis for implementing an externality tax on ownership (e.g. of different breeds).

Insect-based cat and dog food offers a potentially more sustainable feed alternative through reduced land use, water use and emissions compared to animal protein based feeds (Alexander *et al.*, 2017; British Veterinary Association, 2019). One study suggests several insect species to be of greater protein content and digestibility compared to animal and crop by-products commonly found in pet food (Bosch et al., 2014). Alternatively, a technical option to mitigate impacts may be to selectively breed, or use genetic breeding techniques, to produce pets with higher feed efficiencies and lower emissions intensity. Encouragement of pet adoption or re-homing could also reduce demand for breeding new individuals, reduce unnecessary increases in cat and dog populations and mitigate associated environmental impacts.

5 Conclusion: Pet food as an overlooked sub-sector of the food system

The lack of attention that pets have received regarding environmental sustainability is concerning. For example, the mean annual global land use for dry pet food of 49 Mha is approximately twice the land area of United Kingdom (24.2 Mha) (FAOSTAT, 2019). The mean GHG emissions of 106 Mt CO_2 eq would place pet food production, if it were a country as the 60th highest emitter (World Resources Institute, 2014). For comparison, Mozambique and Philippines's total GHG emissions in 2014 were 68.1 and 121.34 Mt CO_2 eq respectively, countries with populations of 26 and 98 million people. The rates of increase in global dry pet food production heightens these concerns, with 11% global growth between 2017 and 2020 (an average annualised rate of 3.5%), led by a 29% growth

(8.9% annually) in Asia Pacific (Alltech, 2020, 2017). As these results only consider dry pet food, the full environmental burden would be increased were the impacts associated with wet pet food and pets fed human leftover food also included.

Given the scale of pet food environmental impacts shown by this study, the current level of debate, research and data surrounding environmental paw print from pets seems disproportionately small. While the lack of detailed global data on pet food constituents has necessitated assumptions to makes these environmental impact assessments, the conclusion that pets play a small but important role in global emissions was robust to variation in these constituent emission intensities. Discussions regarding companion animals are likely to elicit emotive responses and contentious views. Nonetheless, this does not mean their current role and future mitigation options should not be considered and explored. Evidence and calls for the adoption of a human plant-based diets to achieve planetary health and sustainable use of agricultural resources (Clark and Tilman, 2017; Willett et al., 2019) should be extended to feeding the growing number of companion animals, where possible. More controversial will be to include negative environmental externalities in decisions and costs from ownership of companion animal, with a potential role for policy, e.g. a carbon tax on pet foods.

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